Injury, Int. J. Care Injured (2006) **37S**, S41—S50

INJURY
INTERNATIONAL JOURNAL OF THE CARE OF THE INJURED

www.elsevier.com/locate/injury

Vascularised bone grafts for the management of non-union

Panayotis N. Soucacos [a,*], Zoe Dailiana [b], Alexandros E. Beris [c], Elizabeth O. Johnson [d]

[a] *Department of Orthopaedic Surgery, University of Athens, School of Medicine, "K.A.T." Accident Hospital, 2 Nikis Street, 145 61 Kifisia, Athens, Greece*
[b] *Department of Orthopaedics, University of Larissa, School of Medicine, Larissa, Greece*
[c] *Department of Orthopaedics, University of Ioannina, School of Medicine, Ioannina, Greece*
[d] *Department of Anatomy, Histology and Embryology, University of Ioannina, School of Medicine, Ioannina, Greece*

KEYWORDS
Non-union;
Fibular graft;
Vascularisation;
Osteonecrosis;
Fractures

Summary Non-union of the long bones may have severe consequences, particularly when combined with other post-traumatic sequelae, such as tendon adhesions, reflex sympathetic dystrophy and infection, among others. In these cases, it is important to treat the delayed union or non-union first or at the same time with the other problems in order to achieve adequate function. Once the normal bony healing process has been slowed or stopped, it is necessary to provide both stability to the fracture site, as well as a biological stimulus for the fibrocartilagenous callus to finish the healing process. Vascularised grafts, such as the free fibula, offer not only structural support, but also promote bone healing. The later is achieved by trabecular bone formation, as well as vascular sprouting from pedicle vessels.

Introduction

The metaphysis of long tubular bones is comprised primarily of trabecular bone or spongiosa, while the diaphysis contains mostly cortical or lamelar bone. As a result, fracture healing in these complex bony structures is a multifaceted phenomenon. In general, the healing process is initiated principally by the organisation of a blood clot around and between the fracture ends. Eventually, cells originating from the periosteum and endosteum, as well as perivascular cells begin to populate the clot. Subsequently, a wide variety of factors, including mechanical (compression—tension), ionic conditions, pH variations, hormonal factors, play significant roles in the transformation of the initial blood clot to mature bone.[61]

Three phases have been described for fracture healing when there is no surgical intervention. First, is the inflammation phase, which lasts about 10% of the healing time. Secondly, is the reparative phase, which comprises 40% of the healing time and during which the clot is transformed to a mineralised callus

* Corresponding author. Tel.: +30 210 5832 398; fax: +30 210 6280 767.
E-mail address: soukakos@panafonet.gr (P.N. Soucacos).

0020-1383/$ — see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.injury.2006.02.040

which bridges the fractured ends. Lastly, is the remodelling phase, which is a slow and long process that comprises about 70% of the healing process. During this phase, which may take years, the ununited fractured bones are slowly transformed back to normal bone.[8]

Eventually, the initial clot is transformed to callus comprised of fibrocartilage and then to bone by intramembranous and endochondral ossification. Thus, initially woven bone is formed which is subsequently transformed to cortical bone by apposition of the lamelar bone. This type of healing is referred to as secondary healing and occurs when the fractured ends were not initially rigidly stabilised and were not placed under compression. On the other hand, when the fractured bone has been stabilised using the AO principles of internal fixation of fractures with rigid fixation and compression, a direct or primary fracture healing occurs. In primary fracture healing, no cartilage formation is found in the fracture site. Moreover, no visible callus formation is detectable and the fracture line disappears with time.[61]

Many factors may delay or even stop the healing process either leading to extensive fibrocartilage formation in secondary healing or resulting in the formation of fibrocartilage in primary healing. Once this dense tissue fills the fracture site, delayed union or non-union occurs. Among the factors, which have been identified as unfavourable for bone healing, include extensive trauma, bone loss, unstable fixation premature mobilisation, infection, extensive osteonecrosis and old age.[57]

Fracture non-union and delayed union remain serious problems with substantial morbidity.[28] As wound healing is dependent, among other factors, on local tissue vascularity, vascularised bone grafts have been proposed as a means of managing non-union providing means to further assist the healing process by improving the cell-deficient and poorly vascularised environment.

Delayed union and non-union: the role of vascularity

Delayed union is defined as an abnormal slowing of the fracture healing process, which nonetheless will continue to completion with time. Non-union, on the other hand, is defined as a complete cessation of the healing process after about 6—9 months. Thus, the healing process stops in an incomplete state with no potential for complete bony healing to place without intervention.

Radiologic signs of fracture healing may take up to 12 months before becoming evident. Moreover, radiologic signs often appear considerably later than clinically healing. In this regard, the diagnosis of delayed union or non-union is often ambiguous. This, in turn, has resulted in some controversy regarding the time that non-union or delayed union should be diagnosed. Debate on the time elapsed before the diagnosis of delayed union or non-union can be made, is complicated further by the fact that prolonged immobilisation of a delayed union may compromise the functional result. Clinical signs of non-union include motion at the fracture site and pain, while radiographic signs include persistent fracture lines with bone sclerosis, hypertrophic callus formation or atrophic callus formation with bone resorption.

An inadequate blood supply of the fracture site is a primary contributor to the development of delayed union and non-union. Blood supply can be negatively affected by the initial injury, which, in turn, can affect the outcome of the fracture. Thus, extensive trauma, comminuted fractures, damage of the nutrient artery at the time of injury or later as a result of manipulation, large bony defects, excessive periosteal stripping and insufficient stabilisation may lead to delayed union and non-union.[56]

Atrophic non-union is usually attributed to an impaired blood supply. In an animal model of atrophic non-union, investigators assessed the number of blood vessels at the site of an osteotomy using immunolocalisation techniques in both normally healing bones and in atrophic non-union.[32] One week postoperatively, significantly fewer blood vessels were observed in the non-union group, although by 8 weeks the number of vessels had reached the same level as that in the healing group. This findings support the hypothesis that the number of blood vessels in atrophic non-union reaches the same level as that in healing bone, but at a later time-point. In turn, this suggests that early enhancement of diminished vascularity may help prevent non-union of fractures.

Open fractures, high energy and degloving injuries may also be predisposed for delayed union or non-union. This predisposition has been attributed to, in part, to a decreased activity of the fracture exudates, which contains growth factors, such as PGG2, among others.[30] Finally, diaphyseal fractures are more prone to non-union than epiphyseal fractures. This is attributed to the type of bone which is predominately found in these anatomical regions. More specifically, cortical bone, which is located in diaphysis has fewer cells per volume compared to cancellous bone.[80]

Vascularised bone grafts: general issues

Bone grafts are an important part of orthopaedic surgeon's armamantarium. In the extremities, bone grafts are used for the treatment of non-unions and necrotic lesions, for skeletal structural support and for the reconstruction of defects resulting from trauma, tumor excision, osteomyelitis, congenital pseudarthrosis or radiation necrosis. In all cases, their use is successful provided that the host bed has adequate vascularisation. In cases of decreased blood supply, the choice of a vascularised bone graft seems inevitable, as bone grafts with intrinsic blood supply lead to higher success rates and to acceleration of the repair process in the reconstruction of defects and necrotic lesions of the skeleton.[1,4,44–47] The additional advantage of harvesting vascularised bone grafts in combination to skin and/or muscle offers solution to complex problems in skeletal/soft-tissue defect reconstruction.

Vascularised grafts can be classified according to their structure (cortico-cancellous bone, periosteum, epiphysis, joint), size (large, small), donor site (fibula, iliac crest, rib, scapula, distal radius, carpal bones, metacarpals), need for anastomosis (free, pedicled) and combination to other tissues (simple, composite).

The decision to use a free versus a pedicled graft depends upon the location of the recipient site and the potential donor sites in the region, the length of the pedicle and the arc of rotation (to allow approach of the vascularised bone graft to the recipient site in order to bridge the defect),[14] as well as the diameter of the vessels (severe discrepancy between the donor and recipient site vessels, or very small dimensions of pedicles may prohibit the anastomosis). The use of a pedicled graft, harvested from sites nearby the recipient, limits the surgical approach and decreases the length of the procedure due to the absence of anastomoses.

Larger grafts (fibula, iliac crest, rib, scapula) may be combined with skin (osteocutaneus) and/or muscle (osteomuscular graft) that are nourished by perforators through the same pedicle that nourishes the bone graft. Composite grafts provide coverage of bone and soft-tissue defects of the extremities. The most commonly used composite graft is the fibular graft combined with soleus or the flexor hallucis longus muscle and the skin.

Apart of vascularised bone grafts other structures may be transferred, such as the periosteum, the epiphyseal plate, as well as an entire joint.

Vascularised periosteal flaps

Vascularised periosteum is an elastic and flexible membrane with known osteogenic properties that is adaptable to the shape of the recipient area.[76,9] Recent experimental studies showed that the vascularised periosteum is a promising alternative for the reconstruction of small skeletal defects.[13,58,77] The periosteum is able to guide new bone formation and prefabricate bone that is adapted to the recipient defect (Fig. 1).[73,78]

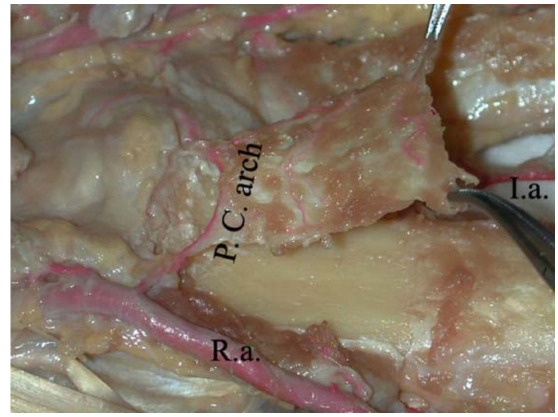

Figure 1 Vascularised periosteal graft from the palmar aspect of the distal radius. The graft is based on the palmar carpal arch (between the radial and the anterior interosseous artery) (Ra, radial artery; PC arch, palmar carpal arch; Ia, anterior interosseous artery).

The use of vascularised periosteum in skeletal defect reconstruction has negligible donor site morbidity.[7] Multiple donor sites have been described, including iliac crest, distal femur, tibial shaft, fibula, 10th rib, scapula, distal humerus, radius and ulna.[11,16,54,14] The vascularised periosteal flap has been successfully applied in the upper extremity for scaphoid non-union, Kienbock's disease, wrist arthrodesis and defects of metacarpals and phalanges.[16,14] Vascularised periosteum has also been used in the lower extremity,[11] the mandible, as well as for avascular necrosis of the talus[16] and femoral head.[79]

Vascularised epiphyseal platetransfer

Vascularised epiphyseal plate transfers offer several advantages for the reconstruction of defects of the growing skeleton, particularly for distal radial defects. Donor sites include the iliac crest, scapula and proximal fibular epiphysis.[71] The proximal fibular epiphysis also offers a joint surface. The transfer of proximal fibular transfer is based on the anterior tibial artery. It provides not only skeletal and joint reconstruction, but also growth potential, as 70% of the fibular growth is expected from the proximal epiphyseal plate.[31,32]

Free vascularised joints

Free vascularised joints have been used in hand surgery. Free vascularised metatarsophalangeal

(MTP) joint is based on the dorsal interosseous artery. It may be transferred to the metacarpophalangeal joints, whereas the second toe proximal interphalangeal (PIP) joint which based on the plantar digital artery, may be used to replace a damaged PIP joints of the hand.[65,20,63] Vascularised joints may be also used from non-replantable digits for the reconstruction of complex hand injuries.[27]

Treatment of delayed union and non-union: the use of vascularised bone grafting

Once the normal fracture healing process has been slowed or stopped, two conditions are necessary in order to establish union. One requirement is stability, which can be achieved by internal or external fixation. The second prerequisite is a biological stimulus for the fibrocartilagenous callus to finish the healing process. One such biologic stimulus is bone graft material. In this regard, fresh autologous bone grafts, particularly cancellous bone, have osteogenetic properties from the cells, which survive the procedure. Osteoconduction reflects the ability of a bone graft to act as a scafold, where osteoblasts from the host are able to synthesise bone through the process of creeping substitution.[17] Osteoconduction, therefore, is the ability of the bone graft to induce bone formation in the bone bed of the lost.

Stability is also a key factor in treating non-unions and it may be achieved by various methods. In most cases of non-union, the treatment of choice is the freshening of the non-united ends with the application of bone grafts followed by stabilisation with internal or external fixation. In cases of non-union related to bone loss and shortening, it is essential to re-establish the bony length for better function of the tendons. This may be achieved by a lengthening procedure using an external fixation device. Once the optimal length has been achieved, then a bone graft, frequently a corticocancelous graft from the iliac crest, can be used to cover the defect. The external fixator may be left in place until full consolidation of the graft.

It is clear that the factors which contribute to delayed union or non-union are complex. Generally, contributing factors can be divided into three major categories: deficiencies in vascularity, deficiencies in the robustness of the chondroosseous response and deficiencies in stability. For a bone graft to enhance bone healing, it must help alleviate the primary causing factor. The various types of grafts used today, ranging from autogenous fresh cancellous to cortical bone and free vascularised grafts, have demonstrated varying capacities to induce active bone formation or to serve as a substrate for bone formation. These capacities are tightly dependent upon the surrounding environment, particularly the mechanical and vascular environment.[69]

The timing and intensity of the immune response differ according to whether a vascularised or non-vascularised graft is being used. Vascularised bone allografts generate significant cell-mediated and humoral responses early on.[34] Experimental findings, such as these support the hypothesis that clinical application of vascularised bone allografts may offer significant advantages over non-vascularised allografts in the reconstruction of massive bone defects. Complications, such as non-union, fracture and collapse of articular segments seen in non-vascularised transplantation may be avoided by preservation of the blood supply to the graft.

Large vascularised bone grafts

Vacularised bone grafts, including fibula, iliac crest, ribs and scapula, have been used to manage recalcitrant post-traumatic shaft non-union of long bones. The vascularised fibular graft can be effectively used for patients with large bony defects and with poor intrinsic stability of the non-union site.[45,47,52] In atrophic non-union without a substantial bone defect, particular of the long bones of the upper extremity, a corticoperiosteal femoral graft can also provide satisfactory results.

Pedicled vascularised bone grafts enables the transfer of bone with preserved circulation and viable osteoclasts and osteoblasts. A useful example is the reverse-flow pedicled vascularised bone graft from the dorsal distal radius.[64] This type of grafting procedure allows for primary bone healing without creeping substitution within the dead bony tissue, and assists in promoting the healing process, replacing deficient bony tissue and revascularising ischemic bone. Advances in the understanding of the anatomy of vascularised pedicled bone grafts have enabled their successful application in managing a variety of carpal disorders, including scaphoid non-unions and Kienbock's disease.[64]

Free vascularised fibular graft

Free vascularised fibular grafting has been proven a valuable tool in the armamentarium of the orthopaedic surgeon, particularly in managing aspectic or infected non-unions with an impressive success rate.[24,45,47] In most cases, these non-unions are complicated with previous surgical procedures,

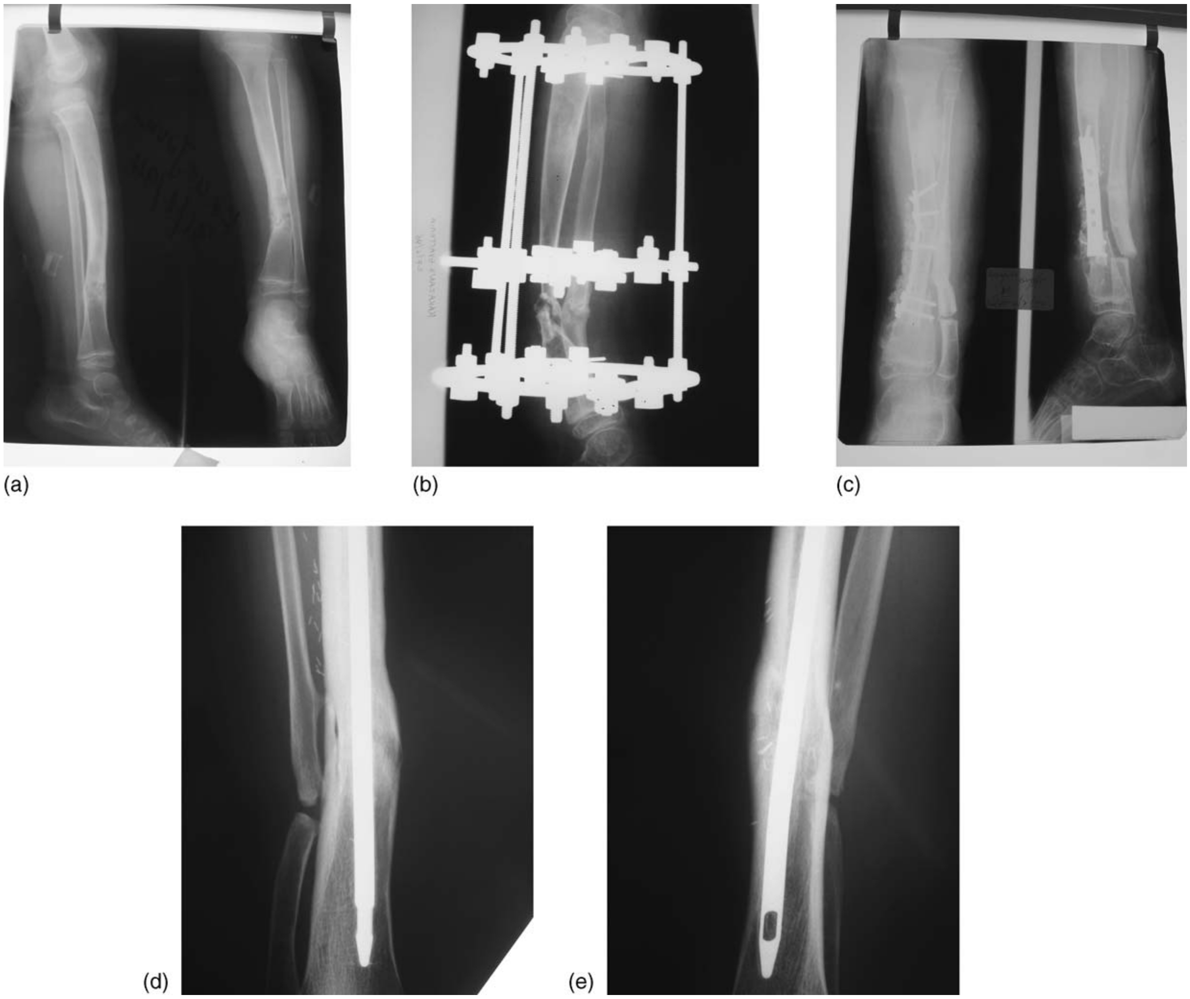

Figure 2 (a) Congenital pseudoarthrosis of the distal third of the tibia in a 3-year-old girl. (b) Various surgical procedures, all of which failed, were attempted to treat the congenital pseudoarthrosis of the tibia. Shown here is an external Ilizarov fixator that was attempted at age 5 years and which also failed. (c) After the previous failures, a vascularised fibular graft was used to treat the pseudoarthrosis (age 7 years). (d) Anteroposterior and (e) lateral radiographs showing complete healing and remodelling of the tibia with full incorporation of the fibular graft 7 years postoperatively. The IM nailing was used to treat a recent proximal fracture of the tibia.

bone atrophy, damage to the surrounding soft tissues, as well as focal infection. These problematic cases require thorough bone and soft tissue debridement, before bridging of the bony defect with the vascularised fibula graft. Various modalities of internal fixation can be used, depending on the host bone. It is important to note, however, that with vascularised fibular grafting, careful monitoring of circulation and early intervention surgery is necessary to avoid vascular failure (Fig. 2).

With the use of free vascularised fibula grafting, Safoury successfully managed infected non-unions and segmental defects of both the radius and ulna that had failed to resolve with conventional treatment.[60] The ipsilateral fibula was used as an osseous or osseocutaneous free flap to reconstruct the radial, but not the ulnar, continuity. Reconstruction of the radius provided a stable forearm, and use of the vascularised fibula graft enable fracture union with good soft-tissue healing and resolution of infection. Vascularised bone grafts, including fibula, femur and scapula, were also effectively used to treat patients with recalcitrant post-traumatic humeral shaft non-union.[50]

Vascularised iliac crest

The iliac crest bone graft, is a cortico-cancellous graft, based on the deep circumflex iliac artery and it is mainly used as a free graft. Because its shape is not adaptable to the long bones of the extremities or the smaller bones of the hand and wrist, it has relatively restricted applications. However, the free vascularised iliac crest has been used for the treatment of scaphoid non-unions (free vascularised or conventional graft) combined with vascular bundle implantation into the non-union[53,21,19] and the reconstruction of skeletal defects of the upper and lower extremity.[26,39] The use of a pedicled iliac crest graft has been described for femoral head necrosis and acetabular reconstruction in total hip replacements.[37,18]

Vascularised scapular and rib grafts

Similar to the iliac crest, the vascularised scapular graft is a cortico-cancellous graft with limited applications because of its shape. Although the majority of applications of both iliac crest and scapula grafts are for mandibular recostruction,[35] there are some sporadic reports that describe the use of vascularised scapular grafts in the extremities.[70,82,71]

The rib is a weak, membranous bone with curved shape. As a free vascularised graft (based on the intercostal vessels) the rib presents very limited applications: restoration of hindfoot, reconstruction of post-traumatic and congenital defects and spinal fusions.[1,6,36,43,51,72,75]

Small vascularised bone grafts

Small vascularised bone grafts are commonly used for the treatment of wrist problems (scaphoid non-unions, osteonecrosis of proximal scaphoid and lunate). They are also indicated for the treatment of skeletal defects of the hand, resulting from trauma or infection.[59]

Several authors have described the vascular anatomy and the donor sites of the distal radius, ulna and second metacarpal.[23,62,14,55] Many pedicles have been identified of the dorsal distal radius (1,2 intercompartmental artery; 2,3 intercompartmental artery; fourth extensor compartment artery), palmar distal radius (palmar carpal arch and palmar metaphyseal arch) and dorsal hand (first dorsal metacarpal artery second, third and fourth dorsal metacarpal arteries) with lengths ranging between 0.5 and 3 cm. Pedicles are usually raised with a periosteal strip and/or muscle and their arc of rotation provides dorsal approach to the distal half of the forearm, the wrist and hand to the proximal interphalangeal joints (PIP) and palmar approach to the lower third of the forearm and the wrist.

Distal radius pedicle

The pedicles of the bone grafts harvested from the distal radius have sufficient length for rotation and transition to the carpal bones. In the treatment of scaphoid non-unions the bone graft must have adequate dimensions to fill the gap and restore scaphoid length and specific shape to restore the angulation of the scaphoid, apart of the intrinsic vascularity that will enhance healing-in most series vascularised bone grafts lead to union in 6—12 weeks.[38,44]

The site of the non-union is critical for the selection of the most appropriate bone graft. For the reconstruction of non-unions of scaphoid waist, grafts from the palmar-ulnar aspect of the radial metaphysis, which are based on the palmar carpal artery running on the distal edge of pronator quadratus can be used.[38] For non-unions of the proximal third of the scaphoid, grafts from the dorsal—radial side of the distal radius have been successfully applied.[83,44,68] Finally, bone grafts based on the dorsal wrist capsule[66] and on the ulnar artery[25] may be also used for the treatment of scaphoid non-unions.

In Kienbock's disease vascularised bone grafts have been used for the reconstruction and revascularisation of the lunate. The grafts from the distal radius may be palmar (based on the palmar carpal artery) or dorsal (based on the arteries of the fourth and fifth extensor compartments).[48,49,59,64]

Vascularised carpal bone and metacarpal grafts

Vascularised bone grafts from the scaphoid tubercle and the pisiform may be used for the treatment scaphoid non-unions and for the replacement of the lunate in Kienbock's disease.[33,12] Grafts from the second metacarpal, pedicled on the first dorsal metacarpal artery may be used for defects of the distal radius, carpal bones, metacarpals or phalanges.[14]

Management of non-union in a deprived biological environment: non-union of femoral neck fractures complicated with osteonecrosis

Due to the anatomy of the blood supply to the femoral head as well as contributing biomechanical factors, femoral neck fractures are associated with high complication rates and present a challenge to the orthopaedic surgeon. This is especially true when dealing with patients younger than 50 years old, with whom every attempt should be made to avoid or delay hip arthroplasty.[3,10] This age group, however, presents the highest rates of non-union and osteonecrosis, as the high-energy trauma involved usually leads to significant displacement and a relatively vertical fracture plane.[84] The rates reported in the literature for development of non-union and osteonecrosis in young patients with femoral neck fractures vary widely, although can reach as high as 86%.

It is well known that non-union and osteonecrosis of the femoral head frequently complicate intracapsular femoral neck fractures, hence the term "unsolved fracture" coined by Speed,[67] and "unsolvable fracture" later used by Garden.[22] This is especially true in young patients, where high-energy trauma is usually involved, leading to increased displacement and shearing forces.[84] Treatment with reduction and internal fixation in this patient population is associated with a 0—59% rate of non-union and 19—86% rate of osteonecrosis.[15,74,84] A variety of procedures have addressed the biological factor with use of non-vascularised bone grafts, muscle pedicle vascularised bone grafts, pedicled vascularised bone grafts and free vascularised fibular grafts.[2,4,5,29,40,42,60] The results reported in the literature with use of the existing techniques have been variable.

Simple reduction and internal fixation has been described as a viable solution in selected patients with femoral neck non-union. Wu et al.[81] reported treatment of 11 patients; all non-unions healed after a mean period of 4.6 months, and no osteonecrosis or other complications occurred during a minimum follow-up of 2 years. However, all patients were selected for this procedure after bone scanning had revealed absence of avascular necrosis of the femoral head.

Procedures attempting to revascularise the femoral head have been used in the management of patients with post-traumatic osteonecrosis, or for primary surgery on patients with a high probability of avascular necrosis. These procedures include non-vascularised bone grafting, muscle-pedicle bone grafting, pedicled vascularised bone grafting, and free vascularised fibular grafting.

The poor results reported with use of avascular grafts led to the use of vascularised grafts. A union rate of 72% was reported. Baksi[2] reported use of a muscle pedicle bone graft for treatment of 56 patients with non-union, neck absorption and evident avascular necrosis in 34 cases. Their procedure consisted of non-union site takedown, femoral head decompression, internal fixation and introduction of the muscle pedicle bone graft. They reported satisfactory union in 75% of patients, which reached 82%, if delayed union was included. Femoral head collapse occurred in 6% of the patients with osteonecrosis. Mechanical failure was noted in 16% of cases. Union was achieved in three cases with an adjunctive osteotomy, an indication that vascularised bone grafts and osteotomy, used in combination in our study, may play complimentary roles in this clinical situation.

The finding that blood supply of muscle pedicle bone grafts is unreliable, led to the use of vascularised pedicled bone grafts. Leung and Shen[41,42] described use of a pedicled bone graft from the iliac crest in treatment of 15 patients with femoral neck fractures. Of these only two had non-union, two had delayed union and the rest were neglected fractures. None of the patients had evident osteonecrosis preoperatively. The bone graft was placed with press-fit technique in a trough that traversed the fracture site. Union was achieved in all 15 patients. A similar technique, with the addition of screw fixation of the graft, was used by Hou et al.[29] to treat five patients with neglected fractures. Of these, only two patients had non-union and bone scanning revealed no osteonecrosis. Union was achieved in all five patients within 5 months. This procedure provides the advantages of a vascularised bone graft, without requiring microsurgical anastomoses. The results of these studies, while very satisfactory, cannot be directly compared to ours, as they mainly concern primary treatment of neglected fractures, without the complication of avascular necrosis.

Later, LeCroy et al.[40] published the first report of use of free vascularised fibular grafts in this patient group. They treated 22 consecutive patients with femoral neck non-union and femoral head osteonecrosis after failed internal fixation. Non-union site takedown and correction of neck shaft angle were achieved during reaming and coring of the femoral neck in preparation for the fibular graft. Knowles pins or cannulated cancellous screws provided additional fixation in all cases. They reported very satisfactory results, with union being achieved in 91% of cases (20 out of 22) after a mean period of 9.3 months. The remaining two consolidated after a second procedure involving pedicled vascularised grafting.

The vascularised fibula, placed subchondrally, provides structural support to the articular surface. Revascularisation of the femoral head and bone healing are promoted by trabecular bone formation, as well as vascular sprouting from the pedicle vessels.[25] We have operated on five patients (four males and one female) with non-union of traumatic femoral neck fractures and concomitant osteonecrosis of the femoral head using a combination of subtrochanteric valgus osteotomy, internal fixation and free vascularised fibular grafting.[4] The patients had a mean age of 26.6 years (range 16—37 years) and the mechanism of injury was a motor vehicle accident in all five cases. The femoral neck fracture was subcapital in two patients, transcervical fracture in another two, and a basilar neck fracture in one case. All patients had received initial treatment at other centers. At the time of referral (range 6—16 months), all patients presented with non-union and osteonecrosis of the femoral head. Patients were available for follow-up for a mean period of 65.2 months (range 51—74 months). Osseous union was achieved in all five patients after a mean period of 5.6 months (range 4—8 months). No adjunctive procedures were necessary to achieve union. There were no cases of hardware migration. Progression of osteonecrosis was arrested in three cases.

The achievement of union was associated with a significant decrease in hip joint pain and an improvement of range of motion. Range of motion was near normal in three cases and satisfactory in the remaining two. No significant morbidity was associated with the donor site in any of the patients. In the patient who received a non-vascularised fibular graft, union was also achieved after a period of 8 months, with no progression of the osteonecrosis. The result in the patient with the pathological fracture was excellent as well. Union was achieved within 6 months, with filling out of the cystic space and preservation of the femoral head.

References

1. Adelaar R, Soucacos PN, Urbaniak J. Autologous cortical bone grafts with microsurgical anastomosis of periosteal vessels. Surg Forum 1974;25:487—9.
2. Baksi DP. Internal fixation of ununited femoral neck fractures combined with muscle-pedicle bone grafting. J Bone Joint Surg Br 1986;68(2):239—45.
3. Barrack RL, Mulroy Jr RD, Harris WH. Improved cementing techniques and femoral component loosening in young patients with hip arthroplasty. A 12-year radiographic review. J Bone Joint Surg Br 1992;74(3):385—9.
4. Beris AE, Payatakes AJ, Kostopoulos VK, et al. Nonunion of femoral neck fractures with osteonecrosis of the femoral head: treatment with combined free vascularized fibular grafting and subtrochanteric valgus osteotomy. Clin Orthop NA 2004;35:335—43.
5. Bonfiglio M, Voke EM. Aseptic necrosis of the femoral head and non-union of the femoral head: effect of treatment by drilling and bone-grafting (Phemister technique). J Bone Joint Surg 1968;50A:48—66.
6. Brenner P, Zwipp H, Rammelt S. Vascularized double barrel ribs combined with free serratus anterior muscle transfer for homologous restoration of the hindfoot after calcanectomy. J Trauma 2000;49:331—5.
7. Brownlow HC, Reed A, Joyner C, et al. Anatomical effects of periosteal elevation. J Orthop Res 2000;18:500—2.
8. Buckwalter JA, Cruess RL. Healing of the musculoskeletal tissues. In: Rockwood CA, Green DP, Bucholz RW, editors. Fractures in adults. Philadelphia: JP Lippincott; 1991. p. 181—222.
9. Burstein FD, Canalis RF. Studies on the osteogenic potential of vascularized periosteum: behavior of periosteal flaps transferred onto soft tissues. Otolaryngol Head Neck Surg 1985; 93:731—5.
10. Chandler HP, Reineck FT, Wixson RL, McCarthy JC. Total hip replacement in patients younger than thirty years old. A five-year follow-up study. J Bone Joint Surg Am 1981;63(9):1426—34.
11. Crock JG, Morrison WA. A vascularised periosteal flap: anatomical study. Br J Plast Surg 1992;45:474—8.
12. Daecke W, Lorenz S, Wieloch P. Lunate resection and vascularized Os pisiform transfer in Kienbock's Disease: an average of 10 years of follow-up study after Saffar's procedure. J Hand Surg-A 2005;30:677—84.
13. Dailiana Z, Shiamishis G, Niokou D, et al. Heterotopic neo-osteogenesis from vascularized periosteum and bone grafts. J Trauma 2002;53:934—8.
14. Dailiana ZH, Malizos KN, Urbaniak JR. Vascularized periosteal flaps of distal forearm and hand. J Trauma 2005;58:76—82.
15. Dedrick DK, Mackenzie JR, Burney RE. Complications of femoral neck fracture in young adults. J Trauma 1986; 26(10):932—7.
16. Doi K, Sakai K. Vascularized periosteal bone graft from the supracondylar region of the femur. Microsurgery 1994;15:305—15.
[17] Einhorn TA. Enhancement of fracture healing by molecular or physical means: an overview. In: Brighton CT, Friedlaender GE, Lane JM, editors. Bone formation and repair. Rosemont, IL: AAOS; 1994.
18. Eisenschenk A, Lautenbach M, Schwetlick G, et al. Treatment of femoral head necrosis with vascularized iliac crest transplants. Clin Orthop Relat Res 2001;386:100—5.
19. Fernandez DL, Eggli S. Non-union of the scaphoid: revascularization of the proximal pole with implantation of a vascular bundle and bone-grafting. J Bone Joint Surg-A 1995;77:883—93.
20. Foucher G, Sammut D, Citron N. Free vascularized toe-joint transfer in hand reconstruction: a series of 25 patients. J Reconstr Microsurg 1990;6:201—7.
21. Gabl M, Reinhart C, Lutz M, et al. Vascularized bone graft from the iliac crest for the treatment of nonunion of the proximal part of the scaphoid with an avascular fragment. J Bone Joint Surg-A 1999;81:1414—28.
22. Garden RS. Malreduction and avascular necrosis in subcapital fractures of the femur. J Bone Joint Surg Br 1971;53(2): 183—97.
23. Gelberman RH, Panagis JS, Taleisnik J, et al. The arterial anatomy of the human carpus Part I: the extraosseous vascularity. J Hand Surg-A 1983;8:367—75.
24. Gonzales DPJ, Bartolome DVE, Grana GL, Villanova JF. Free vascularized fibular grafts have a high union rate in atrophic nonunions. Clin Orthop 2004;419:38—45.
25. Guimberteau JC, Panconi B. Recalcitrant non-union of the scaphoid treated with a vascularized bone graft based on the ulnar artery. J Bone Joint Surg-A 1990;72:88—97.
26. Hattori Y, Doi K, Pagsaligan JM, et al. Arthroplasty of the elbow joint using vascularized iliac bone graft for reconstruction of massive bone defect of the distal humerus. Reconstr Microsurg 2005;21:287—91.
27. Hattori Y, Doi K, Takka S, et al. Free vascularized joint transfer from the nonreplantable digit as a free flap for primary reconstruction of complex hand injury. J Hand Surg 2004;29-A:931—5.
28. Hausman MR, Rinker BD. Intractable wounds and infections: the role of impaired vascularity and advanced surgical methods for treatment. Am J Surg 2004;187:44S—55S.
29. Hou SM, Hang YS, Liu TK. Ununited femoral neck fractures by open reduction and vascularized iliac bone graft. Clin Orthop 1993;294:176—80.
30. Hulth A. Current concepts of fracture healing. Clin Orthop 1989;249:265—84.

31. Innocenti M, Delcroix L, Manfrini M, et al. Vascularized proximal fibular epiphyseal transfer for distal radial reconstruction. J Bone Joint Surg 2005;87(Suppl. 1):237—46.
32. Innocenti M, Delcroix L, Romano GF. Epiphyseal transplant: harvesting technique of the proximal fibula based on the anterior tibial artery. Microsurgery 2005;25:284—92.
33. Judet R, Roy-Camille R, Guillamon JL. Traitement de la pseudarthrose du scaphoide carpien par le greffon pédiculé. Rev Chir Orthop Reparatrice Appar Mot 1972;58:699—705.
34. Jupiter JB, Koniuch MP, Smith R. The managment of delayed union and nonunion of the metacarpals and phalanges. J Hand Surg 1985;10A:457—66.
35. Kakibuchi M, Fujikawa M, Hosokawa K, et al. Functional reconstruction of maxilla with free latissimus dorsi-scapular osteomusculocutaneous flap. Plast Reconstr Surg 2002;109: 1238—44.
36. Kanaya F, Tsai TM, Harkess J. Vascularized bone grafts for congenital pseudarthrosis of the tibia. Microsurgery 1996;17: 459—69.
37. Karakurum G, Gulec A, Buyukbebeci O. Vascularized pedicled iliac crest graft for selected total hip acetabular reconstructions: a cadaver study. Surg Radiol Anat 2004;26:3—7.
38. Kuhlmann JN, Minoun M, Boabighi A, et al. Vascularized bone graft pedicled on the volar carpal artery for non-union of the scaphoid. J Hand Surg-B 1987;12:203—10.
39. Kumta SM, Spinner R, Hung LK, et al. Congenital pseudarthrosis of the tibia in adults treated by a free vascularized iliac crest graft. Microsurgery 1994;15:598—603.
40. LeCroy CM, Rizzo M, Gunneson EE, Urbaniak JR. Free vascularized fibular bone grafting in the management of femoral neck nonunion in patients younger than fifty years. J Orthop Trauma 2002;16(7):464—72.
41. Leung PC, Shen WY. Fracture of the femoral neck in younger adults. A new method of treatment for delayed and nonunions. Clin Orthop 1993;295:156—60.
42. Leung PC. New method of hip reconstruction. Orthop Rev 1986;15(1):3—12.
43. Lin CH, Wei FC, Levin LS, et al. Free composite serratus anterior and rib flaps for tibial composite bone and soft-tissue defect. Plast Reconstr Surg 1997;99:1656—65.
44. Malizos KN, Kyrou M, Vragals B, Zalavras H, Soucacos PN. Longstanding nonunions of scaphoid fractures with bone loss: successful reconstruction with vascularised bone grafts. J Hand Surg 2001;26B:330—4.
45. Malizos KN, Beris AE, Xenakis TA, Korobilias AB, Soucacos PN. Free vascularized fibular graft: a versatile graft for reconstruction of large skeletal defects and revascularization of necrotic bone. Microsurgery 1992;13(4):182—7.
46. Malizos KN, Soucacos PN. Pathologic fracture of the scaphoid due to enchondroma: treatment with vascularized bone grafting. Report of a case. J Hand Surg 1998;23A(2):334—7.
47. Malizos KN, Zalavras CG, Soucacos PN, Beris AE, Urbaniak JR. Free vascularized fibular grafts for reconstruction of skeletal defects. J Am Acad Orthop Surg 2004;12(5):360—9.
48. Mathoulin C, Haerle M, Vandeputte G. Vascularized bone graft in carpal bone reconstruction. Ann Chir Plast Esther 2005;50:43—8.
49. Moran SL, Cooney WP, Berger RA, et al. The use of the 4 + 5 extensor compartmental vascularized bone graft for the treatment of Kienbock's disease. J Hand Surg-A 2005;30: 50—8.
50. Muramatsu K, Doi K, Ihara K, Shigetomi M, Kawai S. Recalcitrant posttraumatic nonunion of the humerus: 23 patients reconstructed with vascularized bone graft. Acta Orthop Scand 2003;74:95—7.
51. Nakamura H, Yamano Y, Seki Meta. et al. Use of folded vascularized rib graft in anterior fusion after treatment of thoracic and upper lumbar lesions. Technical note. J Neurosurg 2001;94:323—7.
52. Osterman AL, Bora FW. Free vascularized bone grafting for large-gap nonunion of lang bones. Orthop Clin North Am 1984;15:131—42.
53. Pechlaner S, Beck E. Sanierende operationsverfahren bei scaphoidpseudartrose. Unfallchirurgie 1990;93:150—6.
54. Penteado CV, Masquelet AC, Romana MC, et al. Periosteal flaps: anatomical bases of sites of elevation. Surg Radiol Anat 1990;12:3—7.
55. Pierer G, Steffen J, Hoflehner H. The vascular blood supply of the second metacarpal bone: anatomic basis for a new vascularized bone graft in hand surgery. Surg Radiol Anat 1992;14:103—12.
56. Reed AA, Joyner CJ, Isefuku S, Brownlow HC, Simpson AH. Vacularity in a new model of atrophic nonunion. J Bone Joint Surg Br 2003;85:604—10.
57. Resnick D, Goevgen T, Niwayama G. Physical injury. In: Resnick, Niwayama, editors. Diagnosis of bone joint disorders. Philadelphia: WB Saunders; 1988.
58. Romana MC, Masquelet AC. Vascularized periosteum associated with cancellous bone graft: an experimental study. Plast Reconstr Surg 1990;85:587—92.
59. Roux JL. Vascularized bone transfers in the wrist and hand. Chir Main 2003;22:173—85.
60. Safoury Y. Free vascularized fibula for the treatment of traumatic bone defects and nonunion of the forearm bones. J Hand Surg Br 2005;30:67—72.
61. Schenk RK, Hunziker EB. Histologic and ultrastructural features of fracture healing. In: Brighton CT, Friedlaender GE, Lane JM, editors. Bone formation and repair. Rosemont, IL: AAOS; 1994. p. 117—46.
62. Sheetz KK, Bishop AT, Berg RA. The arterial blood supply of the distal radius and ulna and its potential use in vascularized pedicled bone grafts. J Hand Surg-A 1995;20: 902—14.
63. Shibata M, Yoshizu T, Seki T, et al. Reconstruction of a congenital hypoplastic thumb with use of a free vascularized metatarsophalangeal joint. J Bone Joint Surg 1998;80A: 1469—76.
64. Shin AY, Bishop AT. Pedicled vascularized bone grafts for disorders of the carpus: scaphoid nonunion and Kienbock's disease. J Am Acad Orthop Surg 2002;10:210—6.
65. Singer DI, O'Brien BM, McLeod AM, et al. Long-term follow-up of free vascularized joint transfers to the hand in children. J Hand Surg 1988;13A:776—83.
66. Dailiana ZH, Malizos KN, Zachos V, Vartimidis SE, Hantes M, Karantanas A. Vascularized bone grafts from the palmar radius for the treatment of waist nonunions of the scaphoid J Hand Surg (Am) 2006;3:397—404.
67. Speed K. The unsolved fracture. Surg Gynecol Obst 1935;60:341—52.
68. Steinmann SP, Bishop AT, Berger RA. Use of the 1 2 intercompartmental supraretinacular artery as a vascularized pedicle bone graft for difficult scaphoid non-union. J Hand Surg 2002;A27:391—401.
69. Stevenson S. Enhancement of fracture healing with autogenous and allogeneic bone grafts. Clin Orthop 1998;355: S239—46.
70. Sundine MJ, Sharobaro VI, Ljubic I, et al. Inferior angle of the scapula as a vascularized bone graft: an anatomic study. J Reconstr Microsurg 2000;16:207—11.
71. Teot L, Giovannini UM, Colonna MR. Use of free scapular crest flap in pediatric epiphyseal reconstructive procedures. Clin Orthop Relat Res 1999;365:211—20.
72. Thoma A, Heddle S, Archibald S, et al. The free vascularized anterior rib graft. Plast Reconstr Surg 1988;82:291—8.

73. Thomson RC, Mikos AG, Beahm E, et al. Guided tissue fabrication from periosteum using preformed biodegradable polymer scaffolds. Biomaterials 1999;20:2007—18.
74. Tooke SM, Favero KJ. Femoral neck fractures in skeletally mature patients, fifty years old or less. J Bone Joint Surg Am 1985;67(8):1255—60.
75. Tu YK, Yen CY, Yeh WL, et al. Reconstruction of posttraumatic long bone defect with free vascularized bone graft: good outcome in 48 patients with 6 years' follow-up. Acta Orthop Scand 2001;72:359—64.
76. Uddstromer L, Ritsila V. Osteogenic capacity of periosteal grafts. Scand J Plast Reconst Surg 1978;12:207—14.
77. Vogelin E, Jones NF, Huang JI, et al. Healing of a critical-sized defect in the rat femur with use of a vascularized periosteal flap, a biodegradable matrix, and bone morphogenetic protein. J Bone Joint Surg 2005;87A:1323—31.
78. Vogelin E, Jones NF, Lieberman JR, et al. Prefabrication of bone by use of a vascularized periosteal flap and bone morphogenetic protein. Plast Reconstr Surg 2002;109:190—8.
79. Wang Y, Zhu S, Zhao D. Vascularized iliac periosteal transfer for the treatment of avascular necrosis of the femoral head and a new evaluation grading system. Chin Med J (Engl) 1996; 109:441—5.
80. Wilson RL, Carter MS. Management of hand fractures. In: Hunter, Schneider, Mackin, Callahan, editors. Rehabilitation of the hand. St. Louis: CV Mosby Co.; 1984. p. 180—94.
81. Wu CC, Shih CH, Chen WJ, Tai CL. Treatment of femoral neck nonunions with a sliding compression screw: comparison with and without subtrochanteric valgus osteotomy. J Trauma 1999;46(2):312—7.
82. Yadav P, Rajput R. Pedicled transfer of vascularized scapular bone graft to the humerus. Plast Reconstr Surg 2001;107: 140—2.
83. Zaidemberg C, Siebert JW, Angrigiani C. A new vascularized bone graft for scaphoid non-union. J Hand Surg 1991;A16: 474—8.
84. Zetterberg CH, Irstam L, Andersson GB. Femoral neck fractures in young adults. Acta Orthop Scand 1982;53(3):427—35.